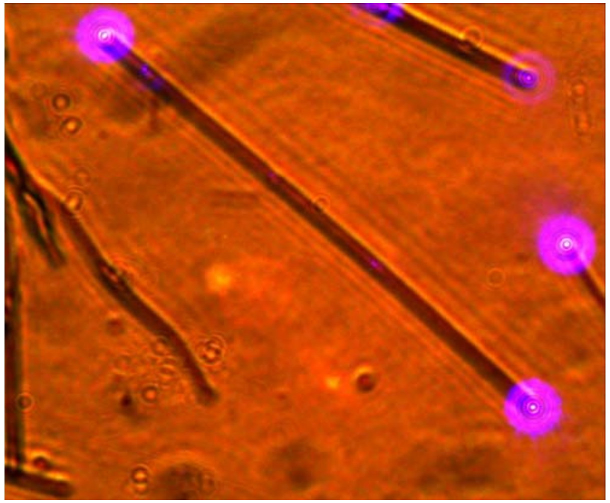
Plasmonic Nanostructures

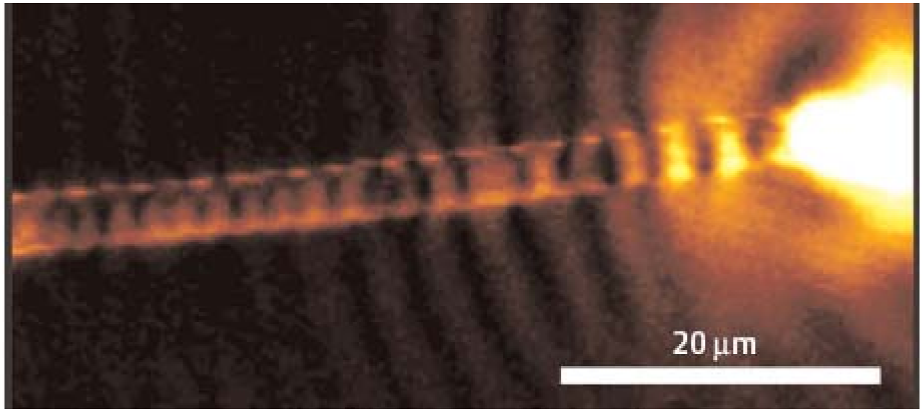
Topics:

1. Introduction
2. Size effects
3. Preparation methods of Nanostructures
4. Carbon-Related Nanostructures (1)
5. Carbon-Related Nanostructures (2)
6. Methods for characterization of Nanostructures
7. Si nanocrystals (1)
8. Si nanocrystals (2)
9. Nanowires
10. Optoelectronics
11. Photonic crystals
12. **Plasmonic nanostructures**
13. Nanostructured solar cells

Nanowire waveguides

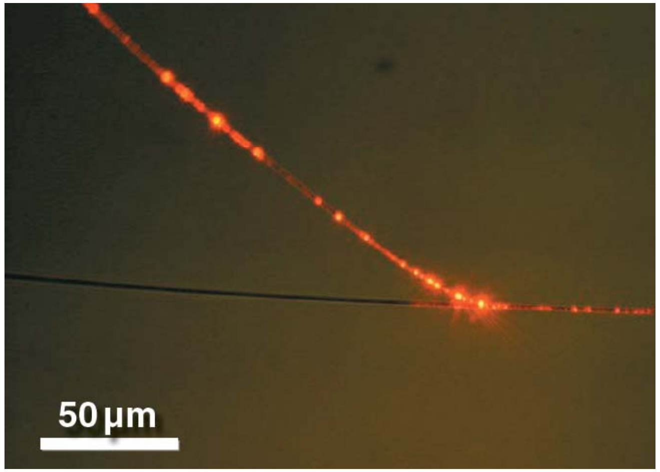


Semiconductor NWs

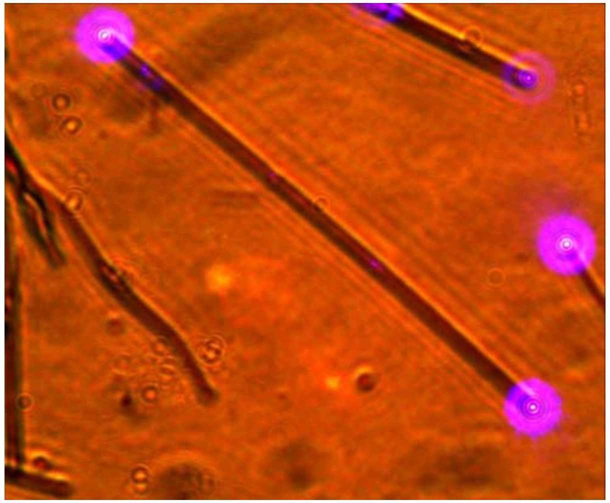


Metal

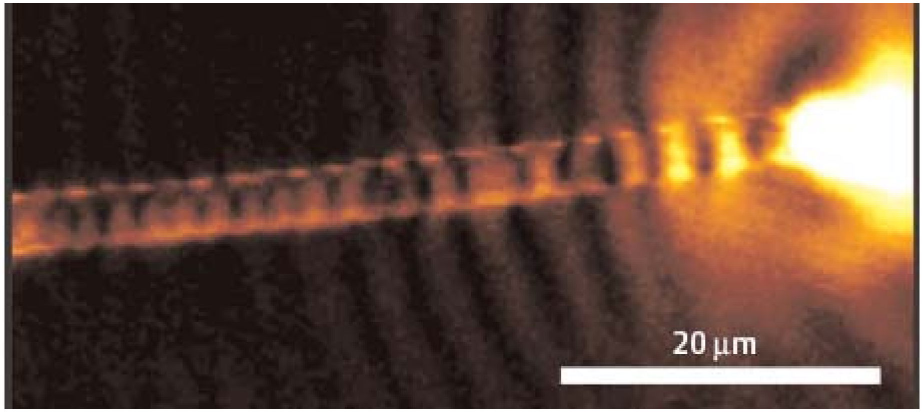
Insulator



Nanowire waveguides

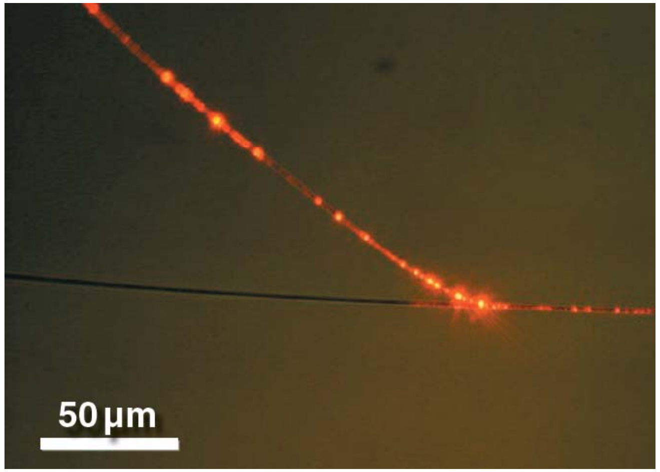


Semiconductor NWs

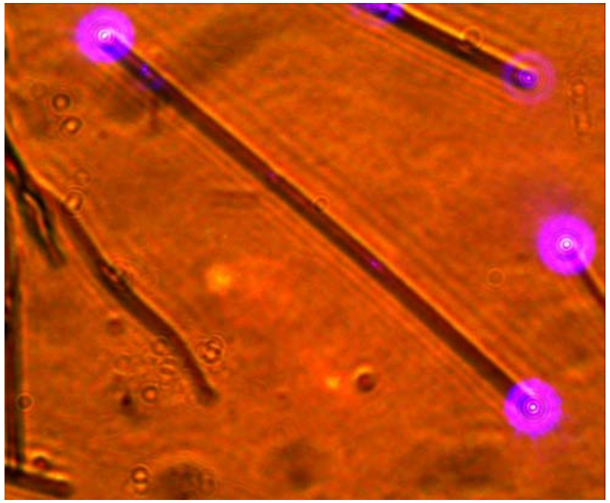


Metal NWs?

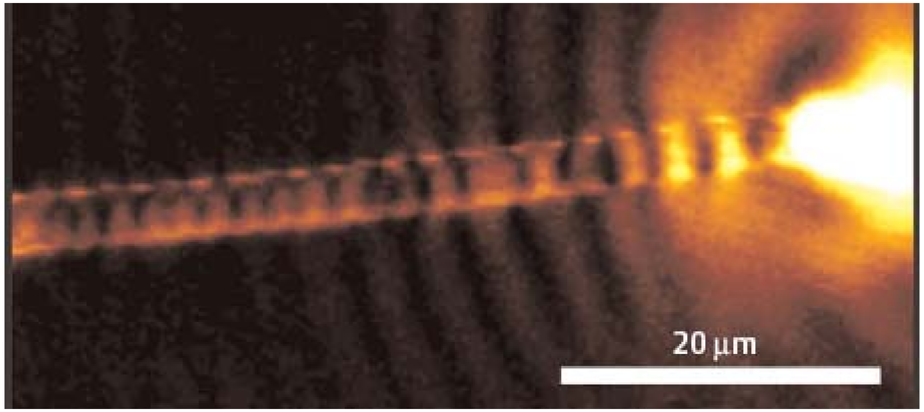
Insulator



Nanowire waveguides

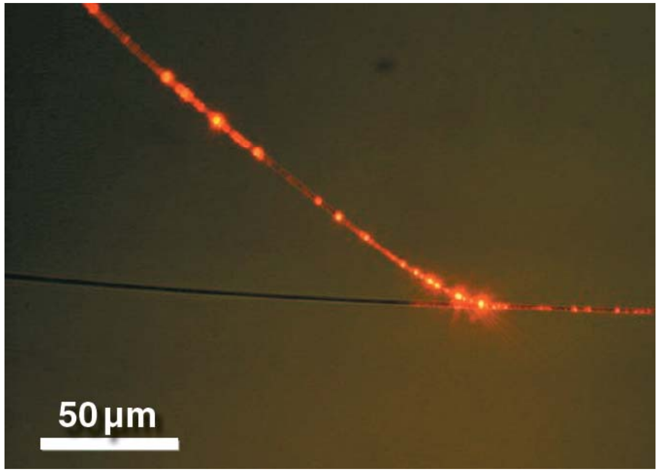


Semiconductor



Metal NWs?

Insulator



Yes !,
but based on
a different principle

Optical properties of metals

Metallic NWs as waveguides for light

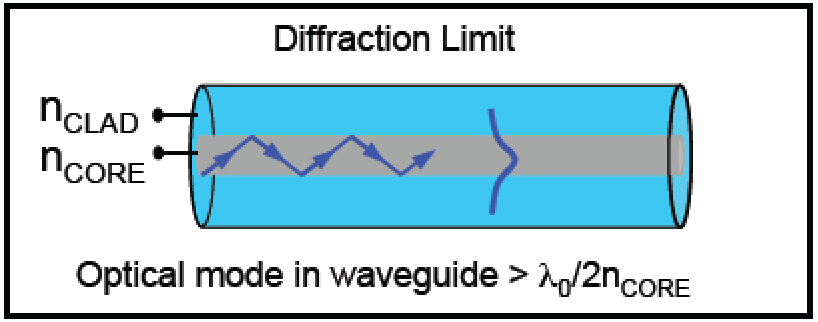
Idea:

direct integration and interaction of electronic and photonic components

Problem: large size mismatch between electronics and dielectric photonics

optical components: $d > \lambda/(2n)$
(diffraction limit)

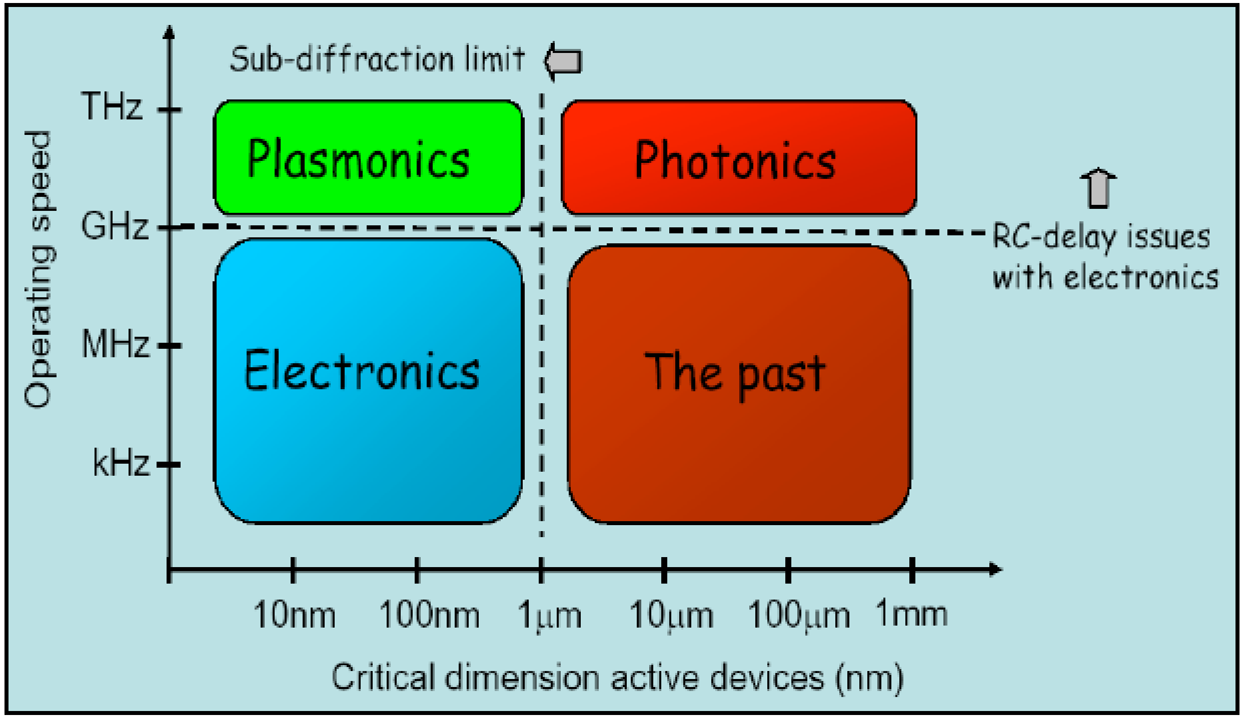
transistors, gates etc. $d \ll 100\,\mathrm{nm}$



optical properties of metals?

The idea of plasmonics

Comparing the Strength and limitations of different technologies:
operating speed and critical dimensions



- Plasmonics will enable an improved synergy between electronic and photonic devices
  - Plasmonics naturally interfaces with similar size electronic components
  - Plasmonics naturally interfaces with similar operating speed photonic networks

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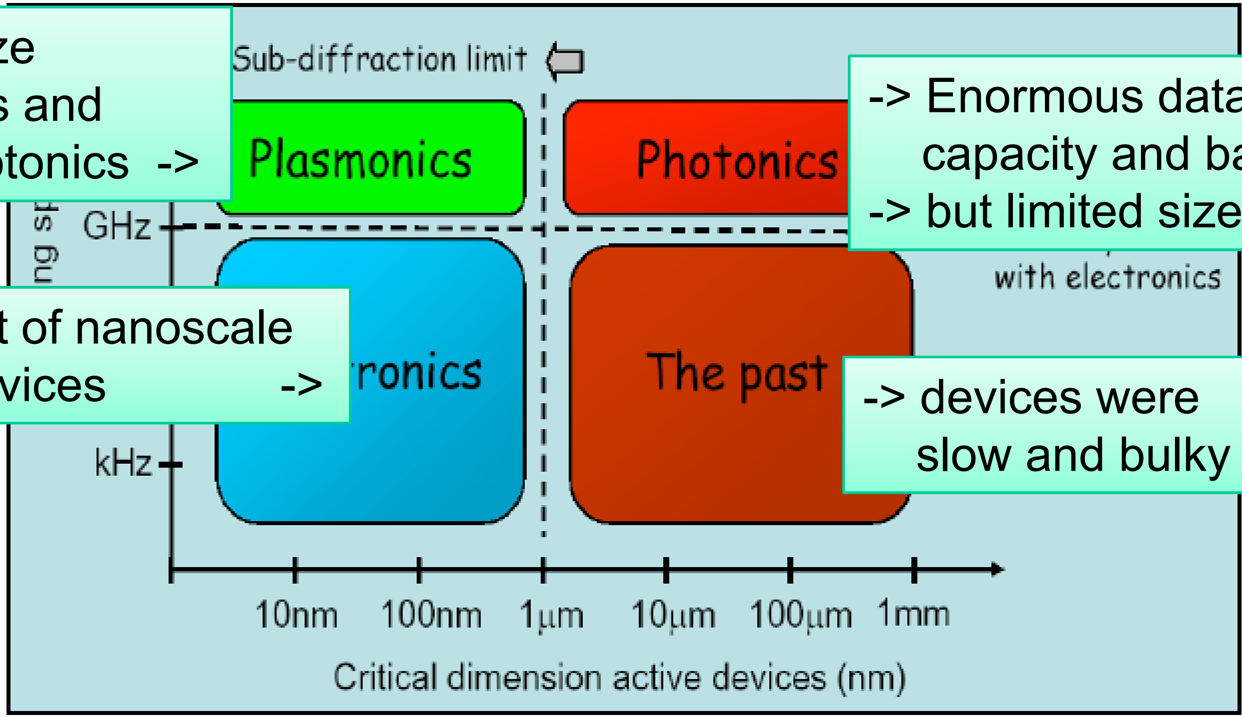
The idea of plasmonics

Photonics as „missing link“ between the two device technologies!?



Offers the size of electronics and speed of photonics ->

-> Enormous data carrying capacity and bandwith
-> but limited size (diffraction limited)

Development of nanoscale electronic devices ->

-> devices were slow and bulky

- Plasmonics will enable an improved synergy between electronic and photonic devices
  - Plasmonics naturally interfaces with similar size electronic components
  - Plasmonics naturally interfaces with similar operating speed photonic networks

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Optical properties of metals

Our model:

free-electron gas

Equation of motion:

$$m\frac{\partial^2 r(t)}{\partial t^2} = -e \cdot E(t)$$

dipole moment:

$$p(t) = -e \cdot r(t)$$

$$\frac{\partial^2 p(t)}{\partial t^2} = \frac{e^2}{m}E(t)$$

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hamonic time dependence:

$$E(t) \sim E(\omega) \cdot \exp(i\omega t)$$

$$p(t) \sim p(\omega) \cdot \exp(i\omega t)$$

$$-\omega^2 p(t) = \frac{e^2}{m} E(t)$$

Optical properties of metals

Our model:

free-electron gas

$$p(t) = -\frac{e^2}{m\omega^2} E(t)$$

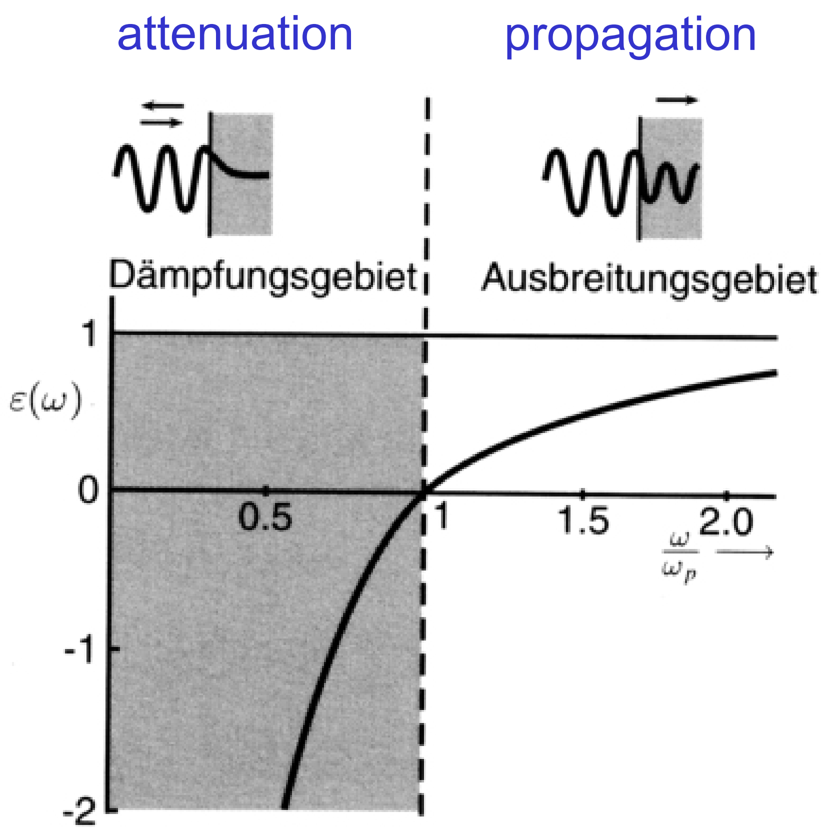
susceptibility: $\chi(\omega) = -\frac{Ne^2}{m\omega^2}$

dielectric constant: $\varepsilon(\omega) = 1 + \chi(\omega) = 1 - \frac{Ne^2}{m\omega^2} = 1 - \frac{\omega_p^2}{\omega^2}$

plasmon frequency: $\omega_p^2 = \frac{Ne^2}{m}$ -> rapid oscillation of the electron density in a conducting media

N: density of free electrons

Dielectric function of a metal

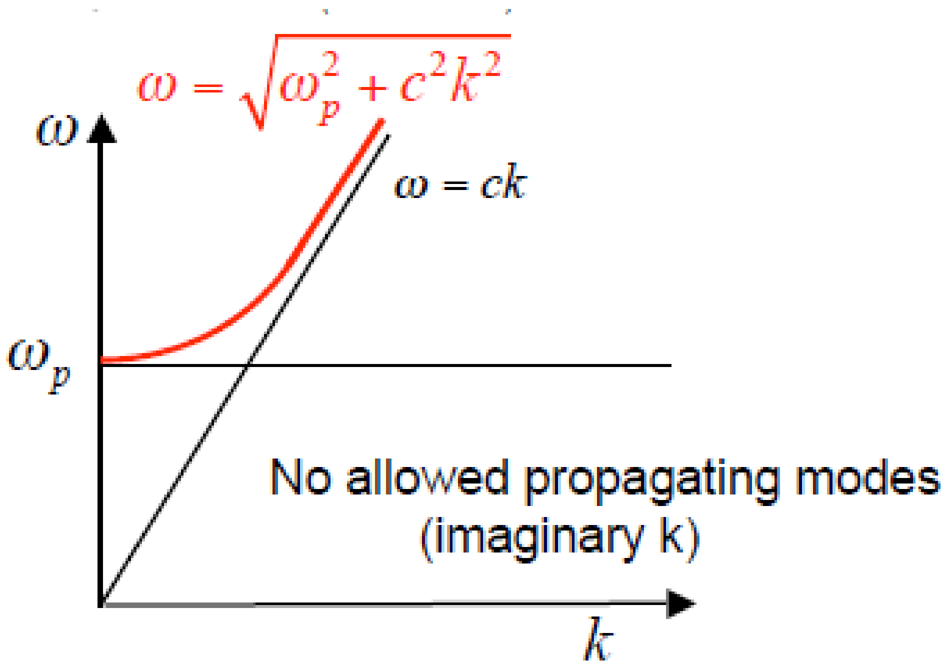


$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

Metals:

- mirrors in the visible
- UV transparency

Dispersion relation

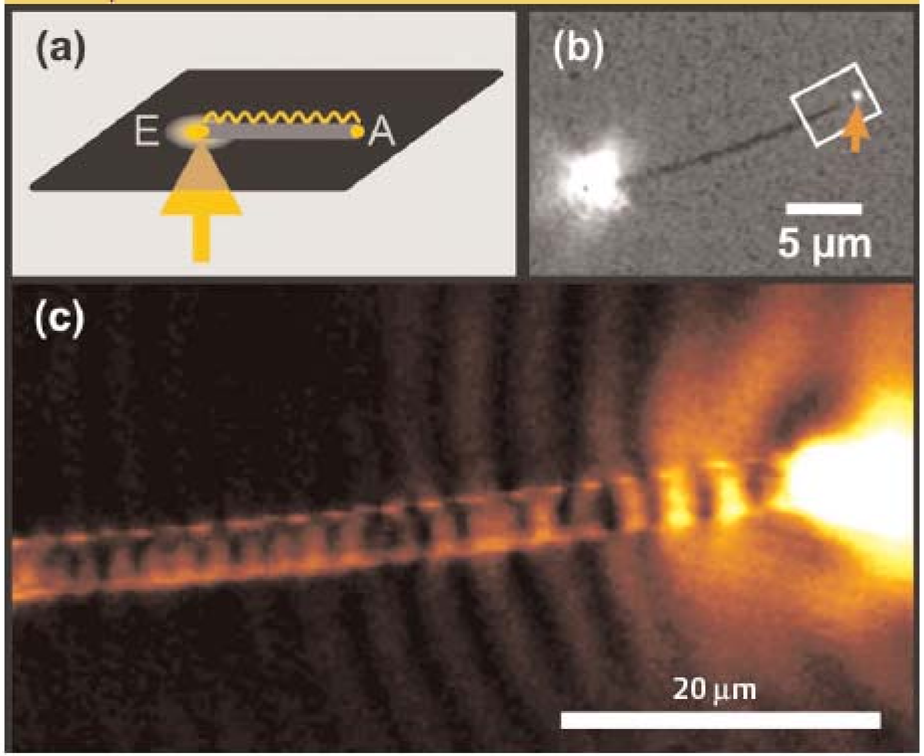


Metals:

- mirrors in the visible
- UV transparency

Metal nanowires

ABB. 8 | LICHTTRANSPORT IM EINKRISTALLINEN NANODRAHT



Plasmonischer Lichttransport in einem einkristallinen Nanodraht aus Silber. a) Fokussiertes Laserlicht (λ = 785 nm) regt am Einkoppel-Ende (E) ein Plasmon an. b) Mikroskopische Aufnahme eines 18,6 µm langen Drahtes. Der kleine Fleck am Auskoppelende (Pfeil) bestätigt den Lichttransport. c) Rasternahfeldmikroskopische Aufnahme des Auskoppelendes. Der am Drahtende reflektierte Plasmonenanteil interferiert mit dem ankommenden Plasmon.

Silver nanowire
infrared light (785nm)

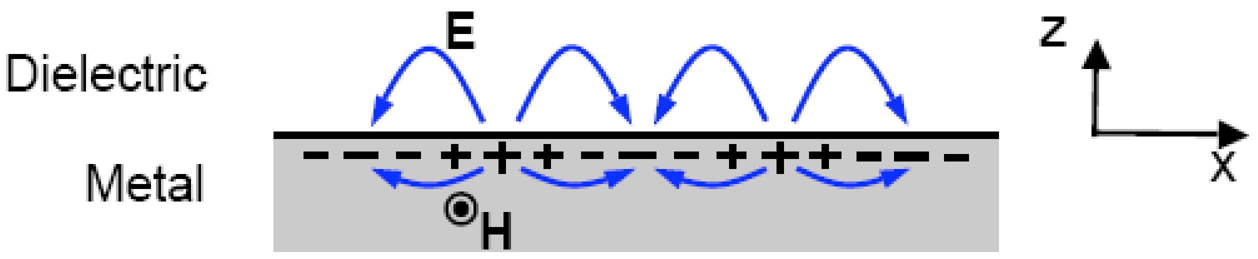
→ cannot be „classical" waveguiding
in the nanowire

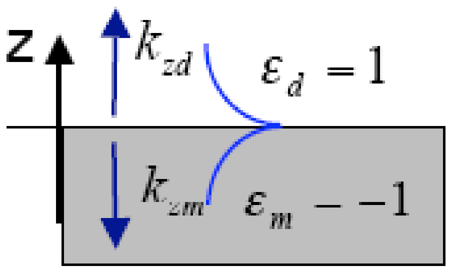
Phys. Unserer Zeit | 5/2006 (37)

Surface Plasmon Polaritons (SPPs)

SPPs: Combined electronic-photonic excitations/particles at the metal-dielectric boundary

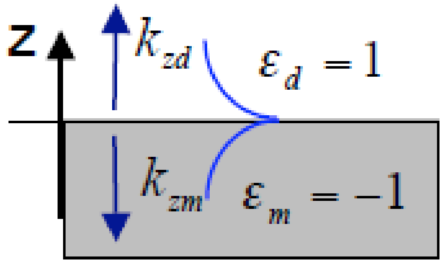
in the metal: longitudinal electron-density waves



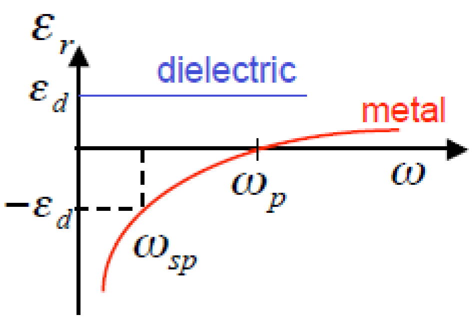


Electromagnetic field intensity is highest at the surface and decays exponentially away from the interface

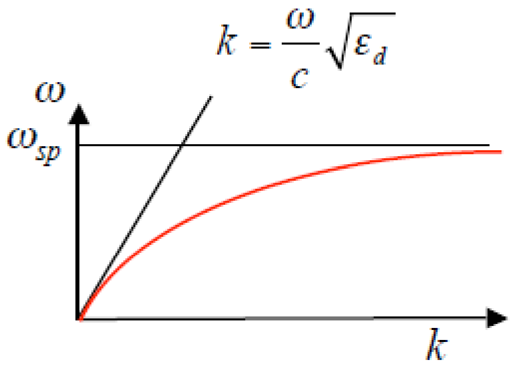
Conditions



$$\frac{k_{zm}}{\varepsilon_m} = \frac{k_{zd}}{\varepsilon_d}$$



$$k_x = \frac{\omega}{c}\left(\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}\right)^{1/2}$$

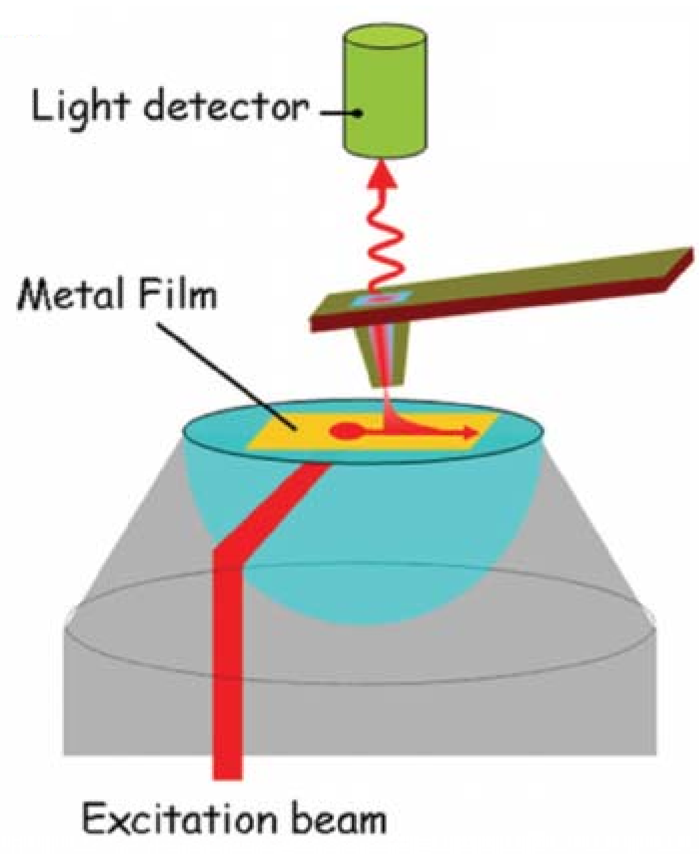


Problem:

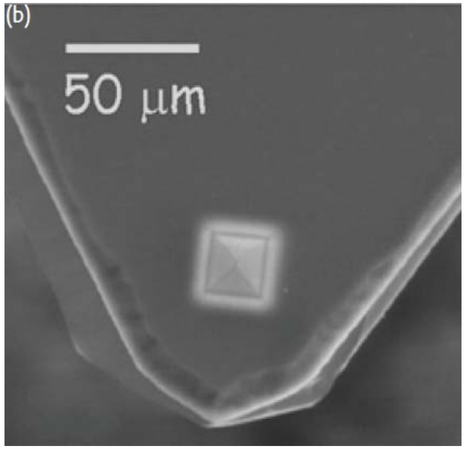
SPPs cannot be directly excited with light!

Imaging of SPPs

Photon scanning tunneling microscope



-> Modified commercially available optical near-field microscope



Cantilever:

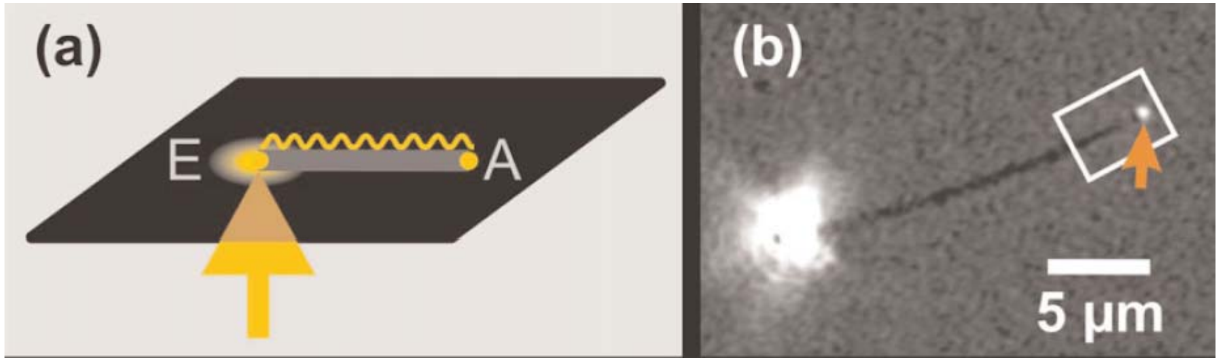
Sharp metal coated tip with itegrated microfabricated glass pyramid

-> opening of the metal film by using e.g. an Focussed Ion Beam milling machine

Optical excitation of SPPs

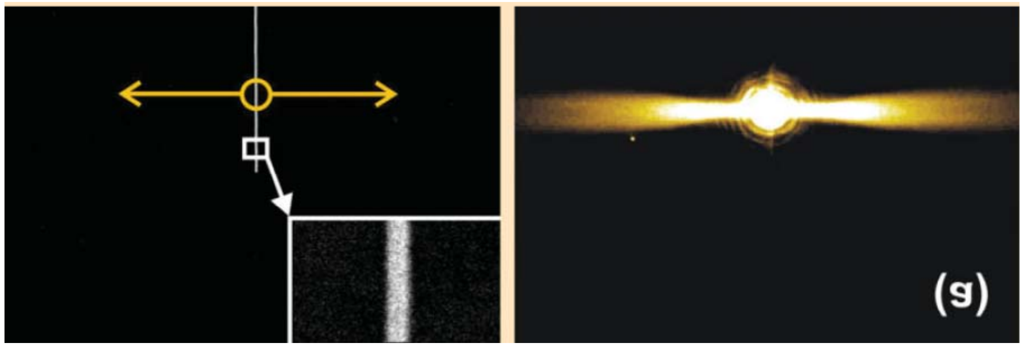
Metallic nanowires

-Excitation at „structural defects“ (-> one end of nanowire)
-Propagation of the plasmon
-Release of light at the other end („structuarl defect)



Metallic nanofilm

-ss an artificial defect a small metallic bar is added on top of the film
-Propagation of the surface plasmon ober long distances in 2 D



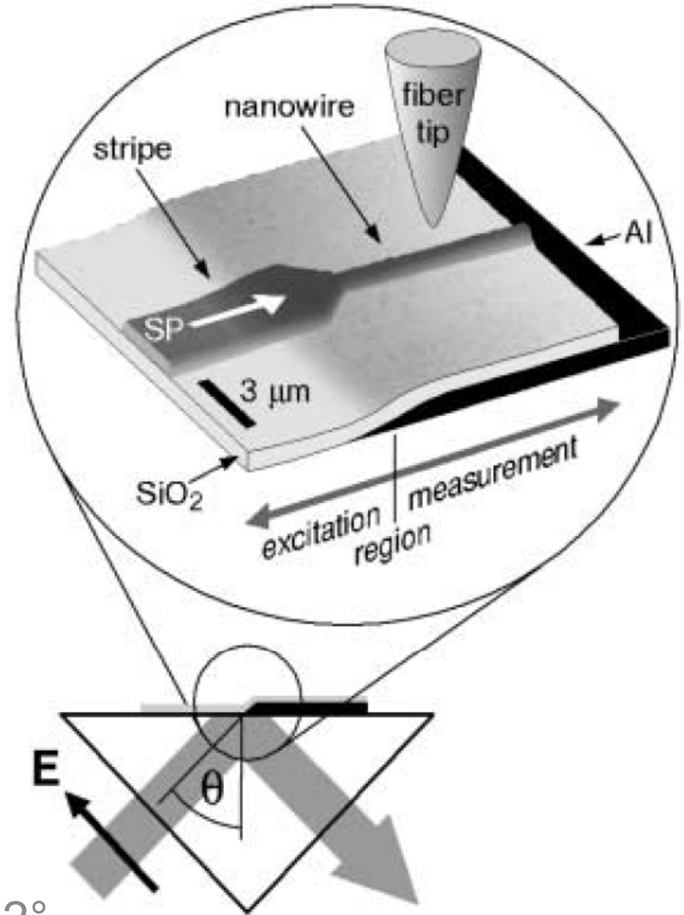
Optical excitation of SPPs

Experimental set-up:

-> multilayerd thin film substrate

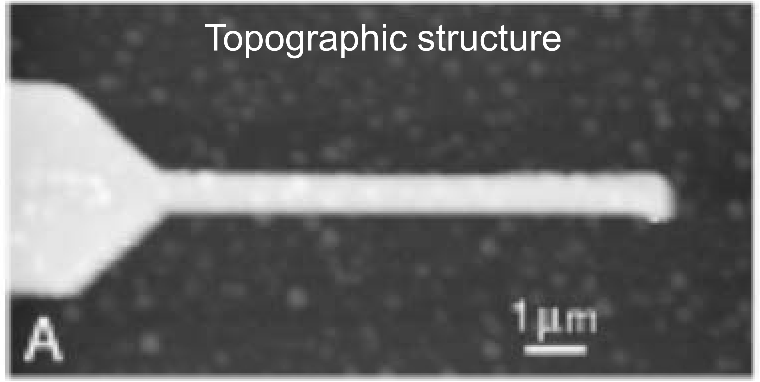
-> SiO_2 as thin dielectric spacer

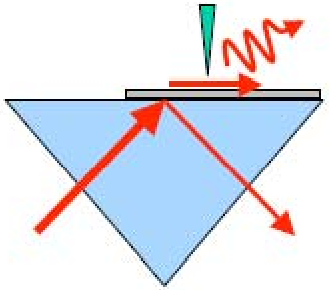
-> first steps towards integrated device structures

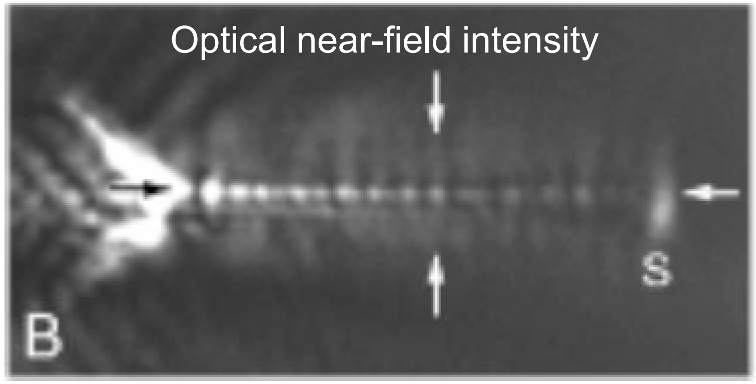


Incident laser beam under 42°

Optical excitation of SPPs





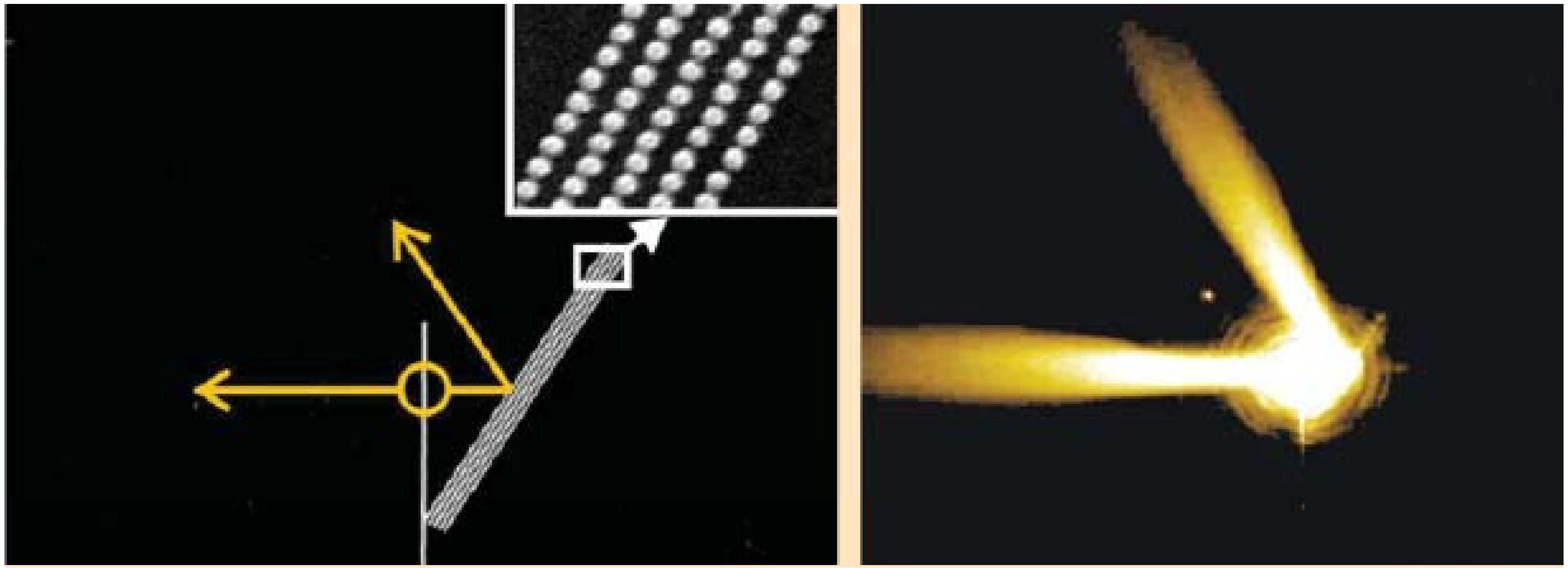


J.R. Krenn et al., Europhys.Lett. **60, 663-669** (2002)

Manipulation of SPPs

-> wave characteristic allows optical phenomena such as reflection of waves, interference and focussing effects

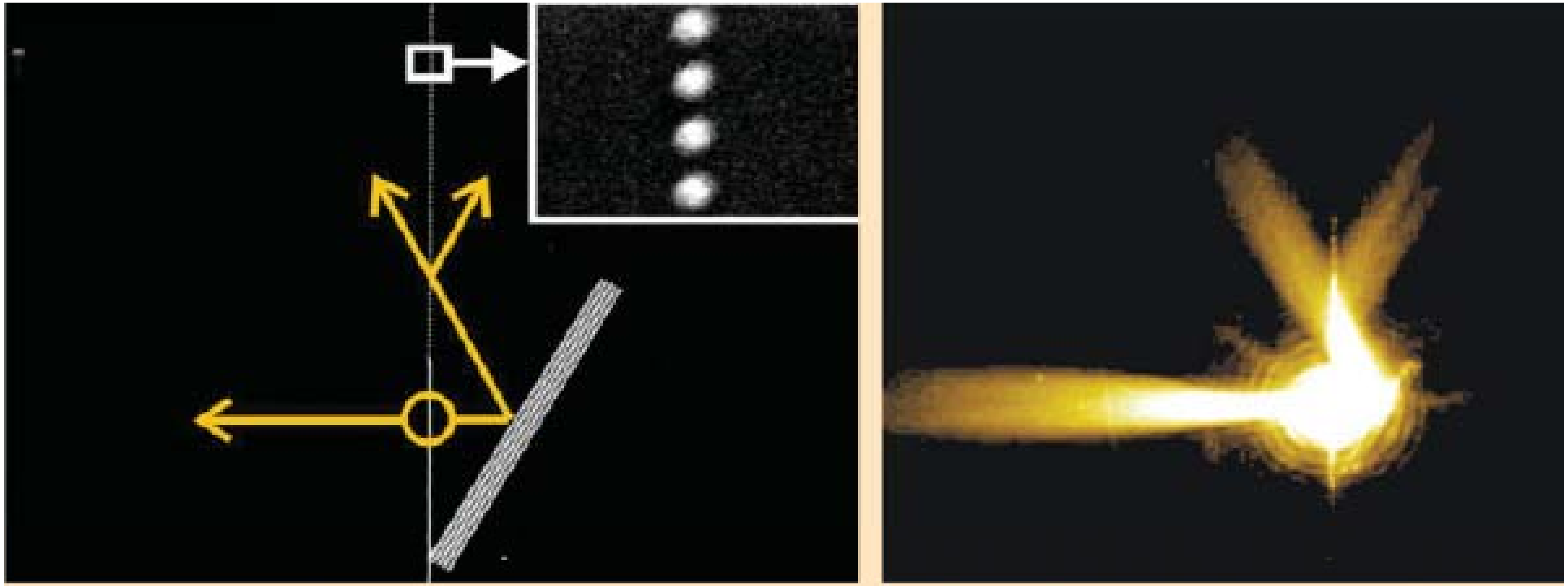
Reflection using a Bragg grating



Bragg grating is achieved by180nm metall NO apparys and can be adjusted by modifying the particle diameters, distances and arrangement.

Manipulation of SPPs

Plasmonic beam splitter



Manipulation of SPPs

Plasmonic interferometer

Structure consists out of 2 Bragg reflectors and 1 beam splitter

Summary SPPs

- electronic/photonic hybrid excitations confined at metal/dielectric interfaces
- propagating along the interface, distance > 1µm
- nm-range field extension at optical frequencies
- complicated excitation schemes to achieve k-conservation